
Understanding the Internet: Model, Metaphor, and Analogy

T. G. McFADDEN

ABSTRACT

THE EFFECTIVE USE, BY STUDENTS AND OTHER USERS, of online and Internet resources depends crucially upon a clear understanding of the form and content of complex electronic networks. Because these networks, and related electronic systems, are often initially unfamiliar even to sophisticated users, it is important that adequate models and analogies be available to support learning and teaching of, and with, these resources. This article discusses some of the obstacles to effective learning inherent in the nature of these systems, and in the ad hoc conceptual tools that many users bring to their understanding of these systems. Particular attention is given to the nature of metaphorical explanation and comprehension in other disciplines, and the ways in which these patterns of understanding can be applied to our interaction with the Internet. Finally, a modest suggestion concerning one kind of metaphor for the Internet is proposed and described for use in classroom instruction.

THE COGNITIVE PROBLEM

What do our students know about the Internet, and when do they know it? For nearly a decade, thoughtful observers of this scene have been arguing that *critical thinking* is the key to successful interaction with online information resources (initially, online catalogs, but more recently the World Wide Web). This should not be news. The problem is that many students at all levels are ill-equipped to deal with abstract concepts of any kind. The concepts of evidence, of authority, of reasoned thought and narrative—and of how these are exemplified in the resources of a library

and can be intellectually exploited—are all quite foreign to a very substantial number of undergraduates. In fact, higher-order conceptual skills of any kind are uncommon for many of our students (McFadden & Hostetler, 1995, p. 224). Oberman (1991) correctly notes that most on-line information retrieval instruction requires students to operate in the realm of the abstract—of metaphor and conceptual models. “In every instance,” she laments, “students must engage in what is most likely unfamiliar cognitive territory” (p. 196). In a recent book on the Internet, Paul Gilster (1997) finds it necessary to make this point repeatedly: “[The] tools are intellectual and attainable, for digital literacy is about mastering ideas, not keystrokes” (p. 15).

What is worse, most students have no idea that they are in trouble. This is a pipeline problem. At the secondary-school level, where the application of technology to instruction is often a vital school reform component, the focus still seems to be on information tools—that is, hardware—instead of on the cognitive processes needed to evaluate and use the information (Tyner, 1998, p. 86). This seduction of the innocent by the glamour of computers and the Internet results in a strong tendency among students to concentrate on the merely technical aspects of successful WWW use and on the details of various search protocols rather than on developing thoughtful methods for understanding the nature of their interaction with the network. Oberman (1991) found, to her dismay, that “numerous studies . . . suggest that some students view the online environment as a means of circumventing traditional mechanisms for understanding the relationships between their information needs and information resources” (p. 196). In other words, they would rather *do* than think about what they are doing. The online environment itself creates the most significant obstacle to comprehension (Martorana & Doyle, 1996, p. 184).¹

But students certainly seem to feel good about their WWW skills. Surveys have indicated repeatedly that most students are very confident about their Internet abilities. In fact, they are nearly as confident about their Internet talents as they are about their knowledge of a vastly less complex online activity, electronic mail (Rumbaugh, 1999, p. 32; Hirt et al., 1999, pp. 22-23). Teachers routinely see this attitude at work in the bored expressions of students in bibliographic instruction classes on the Internet and online information resources. This naïve ignorance is consistent with the mode of learning favored by students as the most common way in which they acquire their largely mythical Internet skills—self-teaching. Again, surveys have indicated that students, especially with respect to Internet use, prefer self-guided and independent methods of learning.

Self-taught students also have greater self-esteem with respect to their Internet skills (Duggan et al., 1999, p. 13). It is revealing that many students and researchers refer to this method of learning as “trial and error” (Davis, 1999, pp. 70-71).²

For most students, indeed for most Internet searchers, the Internet is a typical black box. Very complicated things happen inside of it, but nothing about the box itself reveals what is going on. Our only “window” into the box, the computer monitor screen, is strictly one-dimensional; the scrolling metaphor is singularly apposite here. Unlike a card catalog, which at least provides some physical indication of how large the associated database is—and even sometimes of how it is arranged and therefore accessed—the WWW exhibits no such obvious clues. Sometimes it appears to be incomprehensibly vast, and at other times apparently contains nothing at all; little about the black box suggests an explanation for this seemingly random disparity of results. Even an ordinary book provides more indicators of content and arrangement than the Internet. A book has a front and back, and thus a beginning and ending; it moves, in general, sequentially through a narrative; some things come before and, therefore, introduce other things; some things come after and, therefore, conclude other things. The words and sentences have a context that is physically evident, as well as conceptually manifest; in some books there is a lot of information, and in others not very much.³ But the WWW essentially decontextualizes the ideas that emerge from it upon request (Birkerts, 1994, pp. 122, 123, 129; Van Hartesveldt, 1998, pp. 51-59).⁴ There is no history here, no development of ideas, no context for thinking about why some things are said and other things remain unsaid. For the user of the network, history began about a decade ago, something that is reflected in how disturbingly ahistorical many of our students are.

This is the crux. The Internet is roughly akin to a closed system without external manifestation, rather like a box filled with a substance about which we can only guess the essential properties based on the behavior of pointers and dials on measuring instruments. Students and other searchers of the Internet have cobbled together a whole array of analogies and images to explain how the Internet works. We will find that these metaphors are mostly inadequate or just downright wrong. What we need is a new understanding of the role metaphor plays in our attempts to comprehend and to teach about the Internet to students and to others who are often bereft of the conceptual tools required to grasp highly abstract concepts. Knowing how metaphors, analogies, and models contribute to the successful management of our conceptual lives may provide us with innovative approaches to both learning and teaching about networks.

METAPHORS IN ORDINARY LANGUAGE AND THINKING

Compared to our actual experience of the world, the world in which we live and function is extraordinarily complex and abstract. We begin life, after all, with essentially no awareness that there is any ontological distinction among any of our sensations—everything is “real” and even

the separation between ourselves and everything else is arguably a learned concept. When we finally do begin to make the distinction between what happens to *me* and what happens in the “external” world, our picture of reality divides itself into two—and really only two—parts: there is all of that part of the world that is outside my mind (and perhaps also my body), and there is everything that belongs just to me and does not exist in a public space. We remain aggressively egocentric, but at least not everything exists only in *my* world; there are things that carry on whether we are aware of them or not, and eventually there are also other people who presumably have similar experiences. And, even until fairly late in this development, external things and events are often imbued with life and intention (animism). Thus the great bifurcation in nature that Descartes hardened into a strong and very plausible metaphysics.

It remains true, nevertheless, that the conceptual toolkit we evolve for understanding the world and the events that happen to us is remarkably limited. Certainly our experience of things in space is, at least initially, limited to what our unaided senses provide us. It is no naïve empiricism to suggest that the conceptual framework within which we move about the world is very much informed by our experience of macroscopic objects and events. No word, it has been remarked, is metaphysical without its having first been physical (Hutten, 1954, p. 293). And precisely because we experience objects in space, many of our fundamental concepts are also organized in terms of one or more spatialized metaphors: up/down, left/right, near/far, and so on. These metaphors are not randomly assigned (Lakoff & Johnson, 1980a, p. 464; Garnham, 1999, pp. 45-48).⁵

It follows that our ordinary language and, to a large extent, our technical language, must be inevitably metaphorical. Most of the metaphor embedded in our everyday expressions has been lost—if we ever knew the original meanings in the first place. But we seem to have a signal talent for inventing ways of talking about the unfamiliar in terms of resemblances between new experiences and familiar facts; what is novel is understood by subsuming it under established distinctions (Nagel, 1961, p. 108).⁶ What is even more important, the metaphors that we use are often not merely just a matter of alternative words but contribute importantly to the nature of the things about which we speak: the metaphor sometimes creates the similarity as much as it formulates some similarity antecedently existing (Black, 1962, p. 37).

To illustrate this point, we often speak of a “friendly argument,” but the words we use to talk about arguments in general are anything but friendly. Clearly, the metaphor for an argument for most of us is that of war. We say that “he attacked every weak point,” or that “I demolished his argument,” and even that “she shot down all my arguments.” We talk about “marshaling” the evidence for an argument as though, somehow, military

logistics were involved. In fact, the very earliest uses of this expression had to do merely with lining (usually people) up in some kind of order (as at a feast, for instance), but the military implication occurs in English by the late sixteenth century. Within a short time, however, the metaphoric use had come to mean simply arranging almost anything (material or immaterial) in methodical order; the original use had been lost. It is significant, nonetheless, that the military sense has remained an implicit part of the language of argument—and that, whatever we might say otherwise, this is how we really view the concept.⁷

A metaphor is, therefore, a kind of *pretense*. In using a metaphor, even when the original sense has long since disappeared or been completely assimilated, we are pretending that something is the case when it is not (Turbayne, 1970, p. 13). A good metaphor gives us a stance from which to view something outside the usual limits of our experience; it is most fundamentally, as Kenneth Burke (1945) observed:

a device for seeing something *in terms* of something else. It brings out the thisness of a that, or the thatness of a this. [We] could say that metaphor tells us something about one character as considered from the point of view of another character. And to consider A from the point of view of B is, of course, to use B as a *perspective* upon A. (pp. 503-04)

METAPHORS AND MODELS IN SCIENCE

It should not be surprising that we are strongly inclined to engage in metaphorical expression in talking and thinking about the complex interactive and network systems that we confront in both using and learning from computers. Nor should it be surprising that we are more than sometimes misled by the analogies that we use to understand human-computer interaction. Because these metaphors are often technical analogies for unfamiliar target systems, it will be useful to consider briefly the use of metaphor in scientific explanation.

In the literature of the philosophy of science, as well as that of cognitive psychology, the expression “mental model” is common. An elaborate taxonomy of terms related to this concept has been developed to describe what happens in learning, thinking, and explaining through metaphor (e.g., Gentner & Stevens, 1983). For our purposes, the precise linguistic and conceptual relationships among the ideas of metaphor, analogy, mental model, and conceptual model are not really important. Even the technicians are frequently willing to consider a model to be very similar to a metaphor in ordinary language, although perhaps more detailed and formal (Hutten, 1954, pp. 84, 289, 293). Certainly a model need not be mental in any but the trivial sense that something is “mental” just by virtue of being thought about; we are all familiar with the Tinkertoy constructs chemistry students use to represent molecular structure. Whether we call

it a metaphor, an analogy, a model, or simply an image, what is important here is the *function* of whatever it is that plays this role in our speaking, learning, and thinking.⁸

There is substantial historical disagreement about the legitimate role of models in scientific reasoning, explanation, and prediction.⁹ But there can also be no doubt that historical models of various kinds have strongly influenced the development of sophisticated theoretical concepts. Whether, once elaborated and confirmed, a high-level theory still requires the original model for any conceptual, psychological, or explanatory function is at least debatable. We can learn some important lessons about the role of models in scientific reasoning from a brief consideration of two examples in the history of science: (1) the development of the concept of atmospheric pressure, and (2) the development of the kinetic theory of gases.¹⁰

The Atmosphere as an Ocean of Air

The basic facts concerning what we now call "air pressure" have been known since before the time of Aristotle. We have all experienced trying to draw a liquid up through a tube and finding that, by doing so, we somehow seem to *pull* on the liquid. We know that we can hold the liquid in a tube after we have pulled it up, simply by closing off the top end. Anyone draining a liquid from a barrel, or similar container, is aware that the liquid will not run out unless there is an opening somewhere near the top. Why is this so? Is something actually pulling on the liquid, causing it to move upward? Or is it necessary to open up the top of the container to permit the air pushed out of place by the liquid to find another space to occupy? If the universe were a plenum of some kind, then these phenomena would make sense; no vacuum is possible if there is "stuff" everywhere all the time, just moving around to vacate and fill space as necessary. For centuries, this explanatory idea was known as the Aristotelian principle that "nature abhors a vacuum."¹¹

This same idea could be, and was, applied to explain the action of a suction pump. The use of a simple piston pump to move water from lower to higher places, and in particular to pump water from deep mines, was widespread by the end of the sixteenth century. A crude but effective system of staged pumps in tandem, to raise water to substantial heights, was illustrated by Agricola in his famous 1556 treatise on mining (Conant, 1951, p. 68). Until Galileo, however, no one seems to have called attention to the odd fact that a single pump cannot raise water more than about thirty-two feet. Nature may abhor a vacuum, but why only to this seemingly arbitrary height? Galileo noticed this problem but missed entirely an opportunity to provide the correct explanation. On the first day of the conversations reported in his *Dialogues Concerning Two New Sciences*, Galileo remarked upon this difficulty concerning water raised by a pump; he seemed to regard this as simply a case of a long column of something

unable to support its own weight (just “as if it were a rope”) (Drake, 1974, p. 25). But this is the wrong analogy. It is not the weight of the column of water that is important, it is the weight of something else. It was left to Galileo’s student, Torricelli, to find the right model.

It is important to notice that we do not experience the “weight” of air—certainly not in the same way we experience the weight of water. Visualizing that air exerts pressure from all sides in the same way that water exerts pressure (varying with the depth) requires a leap of the imagination and a selective transfer of properties that are not obviously connected. In a famous letter written three years before he died, Torricelli described us as living “immersed at the bottom of a sea of elemental air” and subject to the resulting atmospheric pressure (Magie, 1935, pp. 70-73). Almost certainly, Galileo also recognized that the atmosphere has weight but apparently did not believe that it exerts a surrounding pressure in the way that water does.

Thinking of the atmosphere as analogous to an ocean, although made up of something much less heavy than water, provides an explanation for the limitations of a suction pump. If it is the weight of the air that pushes down on the water at the bottom of the pumping column, to lift it up as a vacuum is created at the top of the column, then the column of water will be raised only in proportion to the weight of the column of air available to sustain it. This picture lends itself to confirmation by an obvious experiment, the one Torricelli performed in 1643 or 1644 (Middleton, 1964, pp. 29-32) and for which he is now known in every class in elementary physics. If the column of water is sustained at about thirty-two feet by the weight (pressure) of the air, then a similar column of a heavier substance, such as mercury, should be supported in a column at a correspondingly lower level (in this case, at about 2.4 feet). The experiment, performed by Torricelli and his friend Viviani, was an almost perfect success. At one stroke, Torricelli had invented the mercury barometer, the use of mercury as an experimental tool in the study of gases, and a method for producing a vacuum (Conant, 1947, p. 39). But this is only one important consequence of the hypothesis that the atmosphere is like an ocean. The philosopher and scientist Pascal was shortly to articulate, and test, another one.

If the atmosphere is analogous to an ocean, Pascal reasoned, then a short column of air should exert less pressure than a tall one. The explanation does not require a vacuum because none is created in the process simply of moving higher in the atmosphere. The obvious test, then, would be to measure the “weight” of the air (atmospheric pressure) at varying distances from the surface of the earth by discovering whether the mercury in a barometer changes in height as a function of the relative elevation at which the experiment is conducted. Here is Pascal’s own description of the analogy and the inference:

Just as the bottom of a bucket containing water is pressed more heavily by the weight of the water when it is full than when it is half empty, and the more heavily the deeper water is, similarly the high places of the earth, such as the summits of mountains, are less heavily pressed than the lowlands are by the weight of the mass of the air. This is because there is more air above the lowlands than above the mountain tops; for all the air along a mountain side presses upon the lowlands but not upon the summit, being above the one but below the other. (Schwartz & Bishop, 1958, p. 353)

In 1648, Pascal's brother-in-law agreed to carry a mercury barometer to the top of the Puy-de-Dôme in the central mountain range of France. An observer at the foot of the mountain kept constant watch on a similar barometer while various measurements were taken at the summit under diverse conditions. Pascal's predictions were completely vindicated. After all, why should nature abhor a vacuum more at the surface of the earth but less on a mountain top?

The final chapter of this particular tale was written by Newton's contemporary, Robert Boyle. Boyle had heard about Pascal's experiments in the 1650s, even though the publication of Pascal's treatise on pneumatics was delayed until 1663 (Conant, 1957, p. 9). He rightly understood that if Torricelli had offered the correct explanation of the behavior of liquids in the presence of the weight of the air, then this theory should be testable in an artificial vacuum. Significantly advancing the techniques of building air pumps for experimental purposes,¹² Boyle constructed an air pump and receiver to contain a mercury barometer that would respond to air pressure inside the apparatus. Taking this idea to its logical conclusion, Boyle remarked, if "we could perfectly draw the air out of the receiver, it would conduce as well to our purpose, as if we were allowed to try the experiment beyond the atmosphere" (Conant, 1957, p. 19). Not surprisingly, Boyle found the result he had expected: as the quantity of air in the receiver was reduced by the suction pump, the level of the mercury in the barometer correspondingly fell. The Aristotelian *horror vacui* had been dealt a fatal blow.¹³

Good Models

Based on this (paradigmatic) example, can we articulate any general characteristics of "good" cognitive models? Whether a model is "good" or "bad" is very much a matter of what the model is for and for whom it is intended.¹⁴ Various attempts have been made to catalog the features of a good cognitive model (e.g., Mayer, 1989, pp. 59-60; Russon et al., 1994, p. 178). But if we take the most important feature of any particular model to be its *function*, or value, in a given learning situation, then most of the suggested characteristics can be summarized in just two quite general concepts: explanatory power and predictive effectiveness. This conclusion follows directly from the reasonable assumption that the purpose of a

mental model “is to allow the person to understand and to anticipate the behavior of a physical system” (Norman, 1983, p. 12).¹⁵

We must be careful not to identify a legitimate explanation of an event or process only with an analysis in terms of what is already familiar to us.¹⁶ For one thing, what counts as “familiar” to a given individual is very much dependent on time and circumstance. But, more importantly, the development of theoretical physics in the twentieth century has left most of us in the conceptual dust. It may be, as the physicist P. W. Bridgman (1936) argued, that we have lost something in the way of intellectual satisfaction with our theorizing when we can no longer supply an intuitively understandable model of a process or event (pp. 62-63). We may be able to model the process mathematically, but we no longer *really* understand what is going on. Richard Feynman (1964) once remarked that, while he could very well picture invisible angels, he was quite unable to visualize electromagnetic waves (p. 20:9). And certainly beginning with Sir Arthur Eddington’s notorious two tables, the theoretical content of natural science has become increasingly remote from everyday experience—and even from anything we can readily imagine (Nagel, 1961, pp. 45-46; Wolpert, 1992, pp. 1-24).¹⁷

So, an adequate understanding of an event or process, particularly in natural science, probably does not require a conceptual model of the sort I have described to be an essential part of the explanatory apparatus, but it helps. And this is arguably one of the characteristics of a good cognitive model when one is appropriate: in our interpretation of the target system, the elements, and their relationships, in the model should provide some kind of intellectual satisfaction. The metaphorical light bulb turns on. *Now* we get it; before, we did not. Even more importantly, the analogy provides us with an explanation for what we *observe*. If the atmosphere is like an ocean of air in the relevant respects, *then* we can explain why we observe, for instance, that water in ordinary circumstances can only be raised to about thirty-two feet by a suction pump. If a gas does consist of minute perfectly elastic particles, then we can explain why, under given conditions, the sides of a container experience the “pressure” that we actually observe. It may not even matter much whether the analogy is true, only that it consistently yield the correct experimental results.

This brings us to the other important characteristic of a good cognitive model: predictive effectiveness. While a productive analogy interprets what we already know, it must also permit an extension into the realm of what we do not know. A good cognitive model helps organize our experience as we have it, but it also yields implications that are subject to experimental confirmation (or falsification). This is the *heuristic* function of a good metaphor (Borgman, 1986, p. 48; Hutten, 1956, p. 84; Norman, 1983, p. 12; Rickheit & Sichelschmidt, 1999, pp. 19-20). Pascal drew upon this feature of the picture of the atmosphere as like an ocean of air to predict

what would happen when the “weight” of a column of air was varied with altitude—a prediction that was beautifully confirmed. Boyle wondered what would happen if this hypothesis could be tested at an artificial “altitude” (i.e., in a vacuum chamber); his curiosity was rewarded by careful experimentation. In each case, the model provided the appropriate analogical conditions for the test. This is sometimes called the “parallel entailments” feature of a good metaphor (Lakoff & Johnson, 1980a, pp. 457, 460). Certain things true of the model will, by implication, also be true of the target system. If time is money, then time is a limited resource (because money is); if time is money, then time is a valuable resource (because money is) (Lakoff & Johnson, 1980a, p. 457).¹⁸

Alas, there are no time banks, and this brings us to the point at which a metaphor may go bad. A good cognitive model is necessarily selective; only some aspects of the target system are represented by the analogy. The analogy would otherwise be as complex as the target system, providing only a replication of the target system, not a model of it (Toulmin, 1953, p. 165). A useful metaphor suppresses some details and emphasizes others, acting as a kind of filter for our understanding of the target system (Black, 1962, pp. 41-42; Lakoff & Johnson, 1980a, p. 458; Sanford & Moxey, 1999, pp. 57-58). To say that the atmosphere is like an ocean of air is not to say that *all* of our knowledge of the actual ocean should be attributed to the atmosphere. Similarly, to say that the hydrogen atom is like the solar system “clearly does not convey that all of one’s knowledge about the solar system should be attributed to the atom. The inheritance of characteristics is only partial” (Gentner & Gentner, 1983, p. 101). This is where the trouble starts.

Metaphors Gone Bad: Sort-Trespassing and the Internet

It is quite possible, even likely in certain circumstances, to be ill-served by a metaphor. If a metaphor is, fundamentally, the presentation of the facts of one category in idioms appropriate to another (Ryle, 1949, p. 8), then to the extent that the idioms of the analogy are *not* appropriate to the target system, we will be confused by the metaphor. We might be just a little confused, as when we wonder what color are the tiny particles that make up an ideal gas, or whether the objects orbiting the nucleus of the hydrogen atom have mountains or are covered with ice. Or we might be very confused, as was the tourist in Oxford who, after seeing all of the colleges and the Bodleian Library, still asked “But where is the University?” Gilbert Ryle (1949) famously called this error a “category mistake.” Our tourist was mistakenly allocating the university to the same category as that to which the other institutions belong (p. 16).¹⁹ Animistic explanations of physical events are another example of what Turbayne calls “sort-trespassing” (as opposed to legitimate “sort-crossing”). We transfer our experience of how we initiate motion in ourselves to other objects without

having any evidence at all that this is a legitimate analogy (actually, even if the other objects are people). Small children are especially liable to this kind of myth-making (Piaget, 1929, pp. 207ff.).

Words matter here. The way we talk about a target system in terms of a model (especially if we have not made the analogy explicit to ourselves or others) can, to a significant extent, bias the way in which we understand the nature of the target system (Hutten, 1954, pp. 286-87; Russon et al., 1994, p. 178). In an important sense, our conceptual scheme replaces the reality that it is merely intended to model. If our metaphor is seriously out of line with the character of the target system, then we are sort-trespassing in a big way. And we will inevitably follow the associated line of parallel entailments down an increasingly muddled conceptual path. It is arguable that the typical language used to describe the Internet and the World Wide Web is just such a set of sort-trespassing metaphors, and that the implied features of this particular target system are not only wrong but also represent a serious obstacle to a correct understanding of the network and its capabilities. Having the wrong mental model, in this case, is a crucial reason for the inability of many of our students to manage their interaction with the network in a way that reflects any level of critical thinking at all.

The most basic linguistic, and conceptual, mistake that we make about the Internet²⁰ is talking about it as though it were a thing. In fact, we can scarcely do otherwise and say anything at all about it. But, just as Oxford University, unlike its member colleges and other institutions, is not a thing (but we still refer to it that way), so the Internet is, despite our words, not a thing. This is the fallacy of misplaced concreteness. As soon as we get used to talking about the Internet in this way, we are very likely to start saying such other things as “the Internet is a place of learning rather than [just] a technology” and that the Internet is a place to get information (Owen & Owston, 1998, pp. 1, 9). This quite naturally leads to the familiar idea that the WWW is a learning highway (again, a place), and “a pretty super one at that” (Owen & Owston, 1998, p. 260). A natural extension of this line of talk is to describe the Internet as an extremely large database and before you know it, we have rashly described the WWW as “nothing short of the world’s biggest library” (Maloy, 1999, p. 4). It becomes almost irresistible to compare the large Internet search engines to *indexes*, and to refer to them as being like encyclopedias (Owen & Owston, 1998, pp. 73, 81, 87).²¹ Having made that jump to the island of conclusions, like the hapless travelers in *The Phantom Tollbooth*, it is difficult to get off again. If an index to a document, or collection of documents, even pretends to be complete and discriminating (as a good index should), then we might further want to claim that, having used several of the largest Internet search engines, we will “have left few stones unturned” (Owen & Owston, 1998, p. 61).²²

If the WWW is a huge database indexed by the major search engines (that are, moreover, like encyclopedias), then we should expect that an associated array of parallel entailments would emerge from the model to help us understand the Internet and how it functions in information retrieval. If there are such parallel entailments similar to the ones we have noticed in our discussion of other productive models, then this way of understanding the WWW will be confirmed. But it is not.

To begin with, we must not assume that the meaning of "index" intended here is the most elementary sense—i.e., as an indicator or pointer. If it were, then to say that search engines "index" the WWW would be true but trivial. The network user will have something much more complex in mind (but probably never made explicit), largely from experience with indexing and indexes in books, journals, and libraries. Hence, for the model to work, there must be some relevant similarity between this concept and that of "indexing the WWW" by search engines. What does this mean?

Well, it means at least two things that are most certainly *not* true of either the search engines or the "indexed" pages on the WWW: (1) that there has been intelligent intervention in the choice of vocabulary with which to describe target documents,²³ and (2) that the documents themselves have been chosen for inclusion in the database according to some premeditated design (however general). The user of a book index, an encyclopedia, or a journal database has every right to assume that at least these two conditions will obtain information of the document(s) being searched. Nothing about any such collection of documents and document surrogates, however, will help a student understand how the large search engines retrieve pages from the WWW, even under the most carefully crafted search statement. Worse yet, we have included in most of our library WWW sites, parallel with the uncontrolled Internet, databases that do in fact meet the conditions required for proper indexing and vocabulary control (Cook, 1999, p. 11).²⁴ The difference is almost entirely opaque to our readers. It seems fair to conclude that thinking of the Internet as a *thing*, in particular as a thing in important respects like an indexed document collection, is not only a category mistake, but one having clearly pernicious intellectual consequences.²⁵

METAPHORS AND LEARNING: WHY SORT-TRESPASSING MATTERS

Experience and research have abundantly confirmed that the understanding most users have of the complex systems with which they interact is "surprisingly meager, imprecisely specified, and full of inconsistencies, gaps, and idiosyncratic quirks" (Norman, 1983, p. 8). Even college-age students often map erroneous knowledge onto unfamiliar domains. These models may be fragmentary, inaccurate, and even internally inconsistent,

yet they strongly affect a person's construal of new information in the domain. We have already seen how this works with analogies that are inappropriate to the target system; it is not surprising that being ill-served by a metaphor is common and usually implicit. Models, whether correct or incorrect, are carried over in analogical inferencing in other domains (Gentner & Gentner, 1983, p. 126).

The use of metaphor in understanding the unfamiliar, as we have seen, is ubiquitous. Borgman (1986) has argued persuasively that users of complex interactive systems will, in spite of themselves, try to construct some kind of model or analogy to help them understand what is happening to them. But they will not take the time and effort to articulate a *good* model of the system, even if they know what that might be; they just muddle along, never fitting the pieces together (p. 48). I have argued that using a mistaken metaphor for a target system will inevitably lead to incorrect conclusions about the current and future behavior of the system. What if this were not true? What if a bad model of an unfamiliar system is just neutral with respect to understanding and interacting with the system, however counterintuitive that might seem? It would still be important if observation and research indicated that having a good (or better) model of an unfamiliar process or event actually improves retention, learning, and cognitive success with respect to the system. Indeed, there is every indication that this is the case.

There is abundant evidence that familiar analogies can contribute to good instruction (Russon et al., 1994, pp. 178, 184). Mayer (1989) has shown conclusively that having a good conceptual model of a system significantly improves the recall of conceptual information, decreases verbatim retention, and increases creative transfer of knowledge to problem solving in new situations (pp. 43, 49, 58-59). Borgman's own research suggested to her that a model-based approach to training is superior (although only for complex tasks that require some extrapolation beyond basic commands) (Borgman, 1986, p. 59). Pursuing the same line of experimentation, Sparks (1996) concluded that "learners with the most developed mental models, profit most from instruction" (p. 24).²⁶

This may seem like the truism that, the more you know, the easier it is for you to learn. In fact, the idea has a firm theoretical and experimental foundation in the work of cognitive psychologist D. P. Ausabel and his colleagues on the concept of an "advance organizer."²⁷ As the name implies, the idea here is that of a toolkit of relevant information, and an organizing framework, provided to the student prior to the introduction of new or unfamiliar verbal material. Ausabel hypothesized that this approach to learning and retention would improve results over the presentation of unfamiliar verbal material without any advance conceptual warning. Subsequent studies confirmed Ausabel's results (Ausabel, 1960, p. 267; Ausabel, Novak, & Hanesian, 1978). There seems to be clear

evidence that the use of advance organizers, or something functionally equivalent, does contribute to the learning and remembering of complex text information (Mayer, 1979, p. 381; Anderson, Spiro, & Anderson, 1978, p. 439).²⁸ So, while it may be a truism that the more you know, the easier it is for you to learn, it is not trivial.²⁹

CONCLUSION

It may be that we have finally come to a largely negative result. It is undeniable that many students, and perhaps most WWW searchers, bring to their experience conceptual skills and abilities inadequate to the task at hand. The analogical understanding many network users have of the Internet, based on what they say and how they are observed to search and report their results, seems muddled at best and seriously confused at worst. At the same time, numerous studies have shown that how one conceptualizes an unfamiliar target system, what model or metaphor represents the way one thinks about the system, plays a significant role in learning, remembering, and problem solving within and beyond that system. In the philosophy of science, cognitive psychology, and learning theory the concepts of a mental model and conceptual model have been comprehensively studied and elaborated; there can be no doubt about the importance of these tools in thinking and learning at even modestly complex levels.

It may also be true that, in this context, the Internet is more like wave mechanics, string theory, or black holes than anything with which we are even remotely familiar. There just may be no readily accessible metaphor or model for the network that will function for us as mental models do successfully in other areas of thought and experience. It is one thing to compare the Internet to a Big Mac, granny's attic, a soapbox, an information landfill, a yard sale, a gift shop, and junk food—and quite another to say something that can be incorporated into a more formal conceptual picture for teaching and learning.

But there may be some hope. Paul Gilster (1997), in *Digital Literacy*, discusses a variety of ways of thinking creatively about the Internet and search engines for the novice as well as the expert user. He finds that the analogy between the WWW and a library is a limping analogy at best; for this metaphor, the network is still in the dark ages of information retrieval (p. 161). Gilster is willing to compare a search engine to a card catalog only for restricted purposes; the distinction between field-defined and full-text searching illustrates one important difference between a card catalog and a search engine, but one that makes any further comparison of only limited value. The most suggestive metaphor that Gilster (1997) identifies, I think, is the Internet as *operating system* (pp. 239-41). If we can develop an analogy, even if only a thin one, that exploits computing concepts already familiar to most of our students, then at least some of the

characteristics of a good mental model may be available to us to teach more effectively about the Internet. How might this work?

Instead of thinking of the Internet as a place, offers Gilster (1997), maybe it should be thought of as a kind of virtual hard disk or virtual machine (p. 240). What the network (plus a browser) amounts to, metaphorically, is an *environment* (like an office environment). An operating system is not an applications program itself, or a data file or collection of data files, although it links all of these at a particular time for a particular user and a particular machine. The familiar concepts of multitasking, multiprocessing, multithreading, and time sharing all apply, in analogical ways, to the network as we experience it. But perhaps the most important characteristic of an operating system, in this context, is that it is itself a *pretense*.

An important part of the general purpose of a computer operating system is to deceive the user into believing that the actual machine is different in important respects from what it really is. The management of resources is a central function of an operating system (Calingaert, 1982, p. 3); one way the program does this is by creating and presenting a *virtual machine* (and virtual resources) to the user. This has the highly desirable effect of making the programming language of the virtual machine more attractive than that of the original machine (Hansen, 1973, p. 3). The operating system achieves this result, in part, by creating virtual devices and peripherals having a merely logical relationship to the actual system hardware. The user can then concentrate on working with data files and the names of data records, for example, instead of worrying about where any of these things are actually being managed or stored. Virtual memory, imaginary memory spaces, and virtual resources in general are mixed equally with actual memory spaces and programming resources in a way that is completely transparent to the user. All of this happens so quickly that the concurrent processing and multitasking necessary to maintain the pretense is also hidden from the user.

Many of the concepts that we associate with familiar operating systems (e.g., DOS, Windows, OS2) can be applied, *mutatis mutandis*, to the network browser environment. The most important of these, perhaps, is that the operating system is itself devoid of content. It provides a computing and user environment, but it is neutral with respect to what information and programs are selected by the user to function in that environment. An operating system can manage, more or less, false data, incomplete data, faulty programs, and just plain bad information as easily as it can coordinate good data, well-organized files, effective programs, and quality information. This is a crucial feature of the metaphor: an operating system may create, for special purposes, a *virtual disk*, but it makes no claim about the content of the disk; the data on the virtual disk may be flawed, or the intellectual organization may be inadequate to the purpose,

but it is not the job of the operating system to sort out these particular problems. Neither is it the job of the network. So, while some features of an operating system can be mapped onto the Internet, others cannot—just as we have come to expect of productive metaphors. This is, I think, a promising start to developing a conceptual model for the Internet that can be used in instruction.

APPENDIX

The Billiard Ball Model of an Ideal Gas

Boyle also noticed something else during his experiments with the air pump. Air, he said, is distinctly felt to be “springy” in the operation of a compressor or a pump. In either device, the physical sensation one gets is as of pushing or pulling a spring. No such effect is observed in the pumping of water. In fact, if this were not the case, certain kinds of air pumps would not work at all (Conant, 1951, p. 95). Boyle was lavish in his use of metaphor to describe the cause of the springiness of air, the most obvious analogy being a watch spring. He also likened the particles that he assumed made up the atmosphere to a heap of wool bundles that are constantly trying to push out against any attempt to compress them, or to coiled wires of varying lengths unwound from a cylinder and therefore having “springiness” in them (Hall, 1965, pp. 381-382; Conant, 1957, p. 57).

Another way to look at this phenomenon, according to Boyle, is after the manner of Descartes: various kinds of particles are all swirled about in the subtle fluid that fills all of space. Boyle claimed that he was neutral on this issue, although he certainly was an adherent of the corpuscular philosophy (Brush, 1983, pp. 15-16). He apparently was willing, at least in print, to distinguish between the picture of air as an elastic fluid and any particular model by which this characteristic of the atmosphere might be explained (Conant, 1947, p. 47). His discussion, however, clearly anticipates the kinetic theory of gases later developed in the eighteenth and nineteenth centuries.

The typical model of an ideal gas is, at first glance, not so very far from Boyle’s springs (and pulleys and levers). As physicist Norman Campbell (1921) remarked, just the most familiar things in the world to us are objects in motion; it is through motion that anything and everything happens (p. 84).³⁰ We know, in general, what happens when moving bodies collide with one another, or with a fixed object or surface, although we may not know exactly the physical laws describing these reactions. We also know that how a moving object behaves under these circumstances is partly a function of what *kind* of object it is: soft or hard, smooth or rough, round or otherwise. Certain kinds of objects seem to absorb more impact than others: a soft object crushes under impact, while a hard object tends

more to bounce under impact. Some objects seem to give up all of their motion when they strike a surface or another object (think of the familiar child's toy that is four ball bearings suspended in tandem from parallel, horizontal bars).

When we apply these images to a theory of gases, we quickly find ourselves talking about objects like billiard balls, grains of sand, or marbles. And what we already know is quite a lot about the laws of motion of macroscopic elastic spheres of this kind. When physicists speak of a *model* for a theory, generally what they have in mind is a system of things differing chiefly in size from things that are at least approximately realizable in familiar experience (Nagel, 1961, p. 110). This is precisely what the billiard ball model of an ideal gas achieves.³¹ The model gives us an interpretation of the postulates for the kinetic theory of gases in terms of theoretical expressions like "change in the total momentum of the molecules striking a unit surface" (Nagel, 1961, p. 113). We already know from the general laws of dynamics what will be the effect on the motions of the particles of their collisions with each other and with the walls of a container. We can show, therefore, that:

particles such as are imagined by the theory, moving with the speed attributed to them, would exert the pressure that the gas actually exerts, and that this pressure would vary with the volume of the vessel and with the temperature in the manner described in Boyle's and Gay-Lussac's Laws. (Campbell, 1921, p. 82)³²

This way of looking at the properties of a gas and, indeed, of any fluid, eventually gave rise to other questions: How many particles make up a gas of a given volume? How fast do the particles move as a function of temperature? How much mass does each particle exhibit? What exactly is heat? These and similar questions were all approached with an increasingly sophisticated array of mathematical and quantitative experimental techniques in the development of thermodynamics and the chemistry of fluids during the nineteenth century.³³

NOTES

- ¹ There seems no doubt that there is a clear gap between student use of Internet resources and the quality of the resources that instructors expect their students to be using (Grimes & Boening, 2001).
- ² It would be ironic if it turns out that some part, perhaps a significant part, of this cognitive deficit is the result of the early (and uncritical) introduction of computers to children at home and in the schools. See the interesting work of Jane Healy, as reported in Healy (1990) and Healy (1998).
- ³ For an instructive comparison of printed books with the WWW in this context, see McKenzie (2000). Jamie McKenzie has written a great many sensible things about instructional and information technology; anyone interested in the application of technology to the school curriculum should visit his Internet site: <http://www.fno.org/>.
- ⁴ Birkerts's book is a perceptive phenomenology of reading.
- ⁵ We also talk about, for example, an argument as being "solid," a metaphor we bring over from our experience of physical objects and the world of tactile perception: what is

solid is more "real" than what cannot be touched or felt. We ordinarily judge a visual experience to be illusory if we cannot also experience the object in tactile space.

- ⁶ Nowhere is our language more metaphorical than in the ways we speak and write about computers. Consider just this small sample:

backbone
boot
clipboard
number crunching
motherboard (fatherboard?)
daughterboard
desktop
search engine
nesting
surfing
virus

It is instructive, therefore, that perhaps the most frequent model offered for neural and mental activity these days is a *computer*. It would not be surprising if we eventually found "human" characteristics in the behavior of computing machinery; we projected upon computers a highly anthropomorphic vocabulary from the outset. Kenneth Craik started this talk in 1943 with the publication of his brilliant but uneven *The Nature of Explanation*. This important book defended the idea that the brain can be regarded as a kind of calculating machine, and that neurological activity in the brain models the external world as patterns of electrical and chemical activity.

- ⁷ We are not ordinarily inclined to talk about arguments in terms of armored support, supply lines, or air cover. Time may be money, but there are no time banks into which one may make a deposit or from which time may be withdrawn; you can't even get a refund on wasted time (Lakoff & Johnson, 1980a, p. 460).
- ⁸ The contributions to Gentner and Stevens (1983) cover this ground thoroughly for cognitive psychology. For applications in science, see especially Harré (1959), Hesse (1954, 1966, 1967), Hutten (1956), Kargon (1969), Mellor (1968), Miller (1986), and Nagel (1961). For useful discussions of the role of metaphor in philosophy and language, see Beardsley (1967), Berggren (1962, 1963), Black (1962), Lakoff and Johnson (1980), Pepper (1973), and Turbayne (1970).
- ⁹ The *loci classici* are Campbell (1920, 1921), and Duhem (1954).
- ¹⁰ These two examples are very common in treatments of science for the popular market; see, for instance, Conant (1947, 1951) and Derry (1999). For a discussion of the use of analogy in biology, see Canguilhem (1963). The second example is discussed in the appendix.
- ¹¹ While nature may abhor a vacuum, small children apparently do not. If the wind is not blowing in a closed room, then the room is "empty" (Piaget, 1930, pp. 3-31).
- ¹² The history of the development of the air pump as a scientific instrument is briefly sketched in Wolf (1950, pp. 99-109). It is more than appropriate to notice the important contribution to this effort made by Boyle's contemporary, Robert Hooke (Jardine, 1999).
- ¹³ Other implications of the Torricelian hypothesis were also confirmed by experiment. Two very smooth pieces of marble when pushed together, for instance, will "adhere" until placed into an operating vacuum receiver; at a certain point, the stones simply fall apart. An excellent discussion of these experiments in the context of the times is Brett (1944). For a historical and sociological analysis of the controversy between Thomas Hobbes and Boyle on these matters, see Shapin and Schaffer (1985); a more traditional account is Kargon (1966).
- ¹⁴ For instance, the model of electricity as a flowing liquid provides one useful way of understanding the movement of an electric current through a conductor, while the model of electricity as a teeming crowd provides another model for the same phenomenon (Gentner & Gentner, 1983).
- ¹⁵ See also Rickheit and Sichelschmidt (1999, pp. 19-20). The idea is that a good cognitive model should permit its user to "run" the model for additional implications and understanding (itself a metaphor).
- ¹⁶ This is a psychologized version of the Aristotelian requirement that the explanatory premises be "better known" to us than the thing to be explained (*Posterior Analytics*, I.2)

- ¹⁷ The gulf between common sense and the scientific outlook was a persistent theme in Bertrand Russell's popular books on scientific ideas; see especially Russell (1923, 1925).
- ¹⁸ Lakoff applies the concept of metaphorical understanding of the unfamiliar to the realm of mathematics in his analysis of how we acquire mathematical concepts (Lakoff & Núñez, 2000). Parallel entailments are no less important in this context (Lakoff & Núñez, 2000, pp. 56, 64, 68, 92, 97, 367). See also Piaget (1952) and Piaget and Inhelder (1964).
- ¹⁹ Or, as the famous *Blue Guide* to Oxford and Cambridge charmingly observes: "There is no University Building as such, the 'University' being the inward and spiritual grace of which the colleges are the outward and visible forms."
- ²⁰ I will use the terms "Internet" and "World Wide Web" interchangeably.
- ²¹ I don't mean to pick on Owen and Owston here. Their book is generally a sound guide to searching the WWW, especially for secondary-school students; the authors know better than many of the misleading statements I have singled out here. But, as I have emphasized, words matter; once we start sort-trespassing, it is hard to qualify our language to reflect the caution we know is appropriate.
- ²² Of course, I can't leave out the most ubiquitous Internet metaphor of all: "surfing" the 'net. But if the metaphor *surf* from the sports world involves "chaotic movement in a fluid environment with no starting point of destination" (Barker, 1998, p. 262), then the idea of surfing the learning highway in a purposeful way is an instructively mixed metaphor that should be a cautionary tale. We actually know a student who replied, when asked in what database she had found a particular citation: "AltaVista." Nautical metaphors seem to be the trend in describing the WWW. It is becoming fashionable, for example, to talk about the "surface" Web and the "deep" Web. If surfing the WWW is equivalent to getting no further down than the surface WWW, then it is even less true that the largest search engines leave "few stones unturned."
- ²³ Indexing languages based on the language of the indexed text are often contrasted with *controlled indexing languages* (based, for example, on a thesaurus). But, as Hans Wellisch (1995) has argued, "all *indexing* languages, being used for the purpose of rearranging the conceptual structure of natural-language texts in condensed and predictable form are, by definition, controlled" (p. 215).
- ²⁴ This is why the client-server model of the Internet is also flawed: it makes the Internet appear to be one huge database (Devlin, 1997, p. 365).
- ²⁵ The language we use to describe the Internet can have, it turns out, significant legal implications. In the landmark case about Internet filtering in public libraries, *Mainstream Loudoun v. Board of Trustees of the Loudoun County Library* (2 F. Supp. 2d 783), part of the Court's decision rested upon the conclusion that the Internet is more like an encyclopedia than it is like a vast interlibrary loan system. The Court ruled that the defendants misconstrued the nature of the Internet, and found in this regard in favor of the plaintiffs' encyclopedia analogy. The fact that neither metaphor is appropriate would make an interesting law review article.
- ²⁶ Sparks did find, however, that presenting analogies and illustrations together in a learning problem failed to improve model quality as expected; in fact, the reverse was true. He concluded that cognitive overload was the explanatory factor, but the fact that the analogy and the illustration were unrelated to each other may also have contributed to his results (Sparks, 1996, p. 107).
- ²⁷ This kind of filter has an analog in perceptual experience. What we take ourselves to "see," for example, clearly depends on advanced filtering by the brain/mind as a function of prior or simultaneous categorization and inferencing (Bruner, 1957). The work of Jerome Bruner, his colleagues, and his students in the 1950s and 1960s on the role of mental models in perceiving and learning provides a broad and comprehensive theoretical foundation for many of the conclusions reached here. Bruner extended his results to education after the famous Woods Hole Conference on Education in 1959 in a series of important studies of classroom learning and teaching (Bruner, 1960, 1966, 1971). Many of Bruner's most suggestive papers are included in Bruner, 1973; the development of his thinking about these and other matters is engagingly told in his informal autobiography (Bruner, 1983).
- ²⁸ Anderson, Spiro, and Anderson (1978) concluded, however, that although Ausabel was on the right track, the "theoretical justification for the advance organizer is quite flimsy" (p. 439).

- ²⁹ This was, despite widespread misunderstanding, largely the point of E. D. Hirsch's (1987) book about reading and learning.
- ³⁰ Campbell (1920) discusses his own example of the dynamic theory of gases in much greater technical detail (pp. 126-30). Even Newton described his thinking about light in terms of how he noticed the way in which a tennis ball behaves after it has been struck by an oblique racket (Lightman, 1989, p. 97).
- ³¹ And this is why the scientist-turned-philosopher Sir James Jeans (1940) expounded on the billiard-ball model in such elaborate detail in his monograph on the kinetic theory of gases (pp. 12-16).
- ³² The model breaks down when the density is too high or the temperature too low, because other ways in which the gas molecules interact (e.g., they attract each other) then become more important. So the model requires modification for these situations (Derry, 1999, p. 74). This is why the most eminent British physicist of the nineteenth century, Lord Kelvin (1903), remarked that at this level we can speak only of rough approximations to absolute values, not "delicate differential results" (pt II, p. 500).
- ³³ This history is briefly told in Toulmin and Goodfield (1962) and Einstein and Infeld (1938). For a brief chronological survey of the concept of the atom and a literature review, see L. L. Whyte (1961). The correct interpretation of one observational confirmation of the molecular theory of fluids (Brownian motion) was the subject of one of Einstein's famous 1905 papers in theoretical physics.

REFERENCES

- Anderson, R.; Spiro, R. J.; & Anderson, M. C. (1978). Schemata as scaffolding for the representation of information in connected discourse. *American Educational Research Journal*, 15(3), 433-440.
- Ausubel, D. P. (1960). The use of advance organizers in the learning and retention of meaningful verbal material. *Journal of Educational Research*, 51(5), 267-272.
- Ausubel, D. P.; Novak, J. D.; & Hanesian, H. (1978). *Educational psychology: A cognitive view*, 2d ed. New York: Holt, Rinehart, and Winston.
- Barker, S. (1998). Rigour or vigour: Metaphor, argument, and internet. *Philosophy and Rhetoric*, 31(4), 248-265.
- Beardsley, M. (1967). Metaphor. In P. Edwards (Ed.), *The encyclopedia of philosophy* (vol. 5, pp. 284-289). New York: Macmillan.
- Berggren, D. (1962). The use and abuse of metaphor, I. *Review of Metaphysics*, 16(2), 237-258.
- Berggren, D. (1963). The use and abuse of metaphor, II. *The Review of Metaphysics*, 16(3), 450-472.
- Birkerts, S. (1994). *The Gutenberg elegies: The fate of reading in an electronic age*. Boston: Faber and Faber.
- Black, M. (1962). *Models and metaphors: Studies in language and philosophy*. Ithaca, NY: Cornell University Press. Originally published as "Metaphor" in *Proceedings of the Aristotelian Society*, n.s., 55(1954-55), 273-294.
- Borgman, C. L. (1986). The user's mental model of an information retrieval system: An experiment on a prototype online catalog. *International Journal of Man-Machine Studies*, 24, 47-64. See also Borgman, C. L. (1984). *The user's mental model of an information retrieval system: Effects on performance*. Unpublished doctoral dissertation, Stanford University.
- Brett, G. S. (1944). The effect of the discovery of the barometer on contemporary thought. *Journal of the Royal Astronomical Society of Canada*, 38, 7-20.
- Bridgman, P. W. (1936). *The nature of physical theory*. Princeton: Princeton University Press.
- Bruner, J. (1957). On perceptual readiness. *Psychological Review*, 64(2), 123-152.
- Bruner, J. (1960). *The process of education*. Cambridge: Harvard University Press.
- Bruner, J. (1966). *Toward a theory of instruction*. Cambridge: Belknap Press of Harvard University.
- Bruner, J. (1971). *The relevance of education*. New York: W. W. Norton.
- Bruner, J. (1973). *Beyond the information given: Studies in the psychology of knowing*. New York: W. W. Norton.
- Bruner, J. (1983). *In search of mind: Essays in autobiography*. New York: Harper & Row.

- Brush, S. G. (1983). *Statistical physics and the atomic theory of matter from Boyle and Newton to Landau and Onsager*. Princeton: Princeton University Press.
- Burke, K. (1945). *A grammar of motives*. New York: Prentice Hall.
- Calingaert, P. (1982). *Operating system elements: A user perspective*. Englewood Cliffs, NJ: Prentice-Hall.
- Campbell, N. (1920). *Physics: The elements*. Cambridge: Cambridge University Press.
- Campbell, N. (1921). *What is science?* London: Methuen.
- Canguilhem, G. (1963). The role of analogies and models in biological discovery. In A. C. Crombie (Ed.), *Scientific change* (pp. 507-520). New York: Basic Books.
- Conant, J. B. (1947). *On understanding science: An historical approach*. New Haven: Yale University Press.
- Conant, J. B. (1951). *Science and common sense*. New Haven: Yale University Press.
- Conant, J. B. (1957). Robert Boyle's experiments in pneumatics. In J. B. Conant & L. K. Nash (Eds.), *Harvard case histories in experimental science* (pp. 1-63). Cambridge: Harvard University Press.
- Cook, D. (1999). Panning for gold in the cyberstream: The current state of the WWW and the need for teaching evaluation skills. In S. Vincent & S. K. Norman (Eds.), *All that glitters: Prospecting for information in the changing library world* (pp. 3-13). Stamford, CT: JAI Press.
- Craik, K. J. W. (1943). *The nature of explanation*. Cambridge: Cambridge University Press.
- Crombie, A. C. (Ed.). (1963). *Scientific change: Historical studies in the intellectual, social, and technical conditions for scientific discovery and technical invention, from antiquity to the present*. New York: Basic Books.
- Davis, P. (1999). How undergraduates learn computer skills: Results of a survey and focus group. *T.H.E. Journal*, 26(9), 68-71.
- Derry, G. N. (1999). *What science is and how it works*. Princeton: Princeton University Press.
- Devlin, B. (1997). Conceptual models for network literacy. *Electronic Library*, 15(5), 363-368.
- Drake, S. (Ed.). (1974). *Galileo Galilei: Two new sciences*. Madison: University of Wisconsin Press.
- Duggan, A.; Hess, B.; Morgan, D.; Kim, S.; & Wilson, K. (1999). *Measuring students' attitudes toward educational use of the Internet* (Paper presented at the annual conference of the American Educational Research Association, Montreal, April 19-23, 1999). ERIC Reproduction Service Number ED 429 117.
- Duhem, P. (1954). *The aim and structure of physical theory* (P. Wiener, Trans.). Princeton: Princeton University Press.
- Einstein, A., & Infeld, L. (1938). *The evolution of physics: The growth of ideas from early concepts to relativity and quanta*. New York: Simon and Schuster.
- Feynman, R. P.; Leighton, R. B.; & Sands, M. (1964). *The Feynman lectures on physics, vol. 2*. Reading, MA: Addison-Wesley.
- Garnham, A. (1999). What's in a mental model? In G. Rickheit & C. Habel (Eds.), *Mental models in discourse processing and reasoning* (pp. 41-56). New York: Elsevier.
- Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 347-369). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Gentner, D., & Stevens, A. L. (Eds.), (1983). *Mental models*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Gilster, P. (1997). *Digital literacy*. New York: John Wiley & Sons.
- Grimes, D. J., & Boening, C. H. (2001). Worries with the web: A look at student use of web resources. *College & Research Libraries*, 62(1), 11-23.
- Hall, M. B. (1965). *Robert Boyle on natural philosophy*. Bloomington: Indiana University Press.
- Hansen, P. B. (1973). *Operating system principles*. Englewood Cliffs, NJ: Prentice-Hall.
- Harré, R. (1960). Metaphor, model, and mechanism. *Proceedings of the Aristotelian Society*, n.s., 50, 101-122.
- Healey, J. (1990). *Endangered minds: Why our children don't think—and what we can do about it*. New York: Simon & Schuster.
- Healey, J. (1998). *Failure to connect: How computers affect our children's minds—for better and worse*. New York: Simon & Schuster.

- Hesse, M. B. (1954). Models in physics. *British Journal for the Philosophy of Science*, 4, 198-214.
- Hesse, M. B. (1966). *Models and analogies in science*. Notre Dame, IN: University of Notre Dame Press.
- Hesse, M. B. (1967). Models and analogy in science. In P. Edwards (Ed.), *The encyclopedia of philosophy* (pp. 354-359). New York: Macmillan.
- Hirt, J. B.; Bayless, L.; Collins, D.; Dobbins, T.; Fravel, P.; La Boone, K.; La Boone, E.; Lichty, M.; Worth, P.; & Wood, P. (1999). An assessment of computer skill levels among user groups on campus. *College and University Media Review*, 5(2), 11-27.
- Hutten, E. H. (1954). The role of models in physics. *British Journal for the Philosophy of Science*, 4, 284-301.
- Hutten, E. H. (1956). *The language of modern physics*. London: George Allen & Unwin.
- Jardine, L. (1999). *Ingenious pursuits: Building the scientific revolution*. New York: Nan A. Talese.
- Jean, J. H. (1940). *An introduction to the kinetic theory of gases*. New York: Macmillan.
- Kargon, R. (1966). *Atomism in England from Harriot to Newton*. Oxford: Clarendon Press.
- Kargon, R. (1969). Model and analogy in Victorian science: Maxwell and the French physicists. *Journal of the History of Ideas*, 30, 423-436.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.
- Lakoff, G., & Johnson, M. (1980a). Conceptual metaphor in everyday language. *Journal of Philosophy*, 77(8), 453-486.
- Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. New York: Basic Books.
- Lightman, A. P. (1989). Magic on the mind: Physicists' use of metaphor. *American Scholar*, 58(1), 97-101.
- Magie, W. F. (1935). *A source book in physics*. New York: McGraw Hill.
- Maloy, T. K. (1999). *The Internet research guide*. New York: Allworth Press.
- Martorana, J., & Doyle, C. (1996). Computers on, critical thinking off: Challenges of teaching in the electronic environment. *Research Strategies*, 14(3), 184-191.
- Mayer, R. E. (1979). Can advance organizers influence meaningful learning? *Review of Educational Research*, 49(2), 371-383.
- Mayer, R. E. (1989). Models for understanding. *Review of Educational Research*, 59(1), 43-64.
- McFadden, T. G., & Hostetler, T. J. (1995). Introduction. *Library Trends*, 44(2), 221-236.
- McKenzie, J. (1998). Grazing the net: Raising a generation of free-range students. *Phi Delta Kappan*, 80(1), 26-31.
- McKenzie, J. (2000). When the book? When the Net? *From Now On: The Educational Technology Journal*, 9(7). Retrieved August 20, 2001 from the World Wide Web: <http://www.fno.org/mar2000/covmar.html>.
- Mellor, D. H. (1968). Models and analogies in science: Duhem versus Campbell? *ISIS*, 59 (pt. 3, n. 198), 283-290.
- Middleton, W. E. K. (1964). *The history of the barometer*. Baltimore: The Johns Hopkins University Press.
- Miller, A. I. (1986). *Imagery in scientific thought: Creating 20th-century physics*. Cambridge: MIT Press.
- Nagel, E. (1961). *The structure of science*. New York: Harcourt, Brace & World.
- Norman, D. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7-14). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Oberman, C. (1991). Avoiding the cereal syndrome of critical thinking in the electronic environment. *Library Trends*, 39(3), 189-202.
- Owen, T., & Owston, R. (1998). *The learning highway: Smart students and the net*. Toronto: Key Porter Books.
- Pepper, S. C. (1973). Metaphor in philosophy. In P. P. Wiener (Ed.), *Dictionary of the history of ideas* (vol. 3, pp. 196-201). New York: Charles Scribner's Sons.
- Piaget, J. (1929). *The child's conception of the world*. London: Kegan Paul, Trench, Trubner & Co.
- Piaget, J. (1930). *The child's conception of physical causality*. London: Routledge & Kegan Paul.
- Piaget, J. (1952). *The child's conception of number*. London: Routledge & Kegan Paul.

- Piaget, J., & Inhelder, B. (1964). *The early growth of logic in the child*. London: Routledge & Kegan Paul.
- Rickheit, G., & Habel, C. (Eds.). (1999). *Mental models in discourse processing and reasoning*. New York: Elsevier.
- Rickheit, G., & Sichelschmidt, L. (1999). Mental models: Some answers, some questions, some suggestions. In G. Rickheit & C. Habel (Eds.), *Mental models in discourse processing and reasoning* (pp. 9-40). New York: Elsevier.
- Rumbaugh, T. (1999). Computer-mediated communication: Knowledge and behavior of users. *College and University Media Review*, 5(2), 29-36.
- Russell, B. (1923). *The abc of atoms*. London: Kegan, Paul, Trench, Trubner.
- Russell, B. (1925). *The abc of relativity*. London: Kegan, Paul, Trench, Trubner.
- Russon, A. E.; Josefowitz, N.; & Edmonds, C. V. (1994). Making computer instruction accessible: Familiar analogies for female novices. *Computers in Human Behavior*, 10(2), 175-187.
- Ryle, G. (1949). *The concept of mind*. New York: Barnes and Noble.
- Sanford, A. J., & Moxey, L. M. (1999). What are mental models made of? In G. Rickheit & C. Habel (Eds.), *Mental models in discourse processing and reasoning* (pp. 57-76). New York: Elsevier.
- Schwartz, G., & Bishop, P. W. (1958). *The origins of science*. New York: Basic Books.
- Shapin, S., & Schaffer, S. (1985). *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*. Princeton: Princeton University Press.
- Sparks, P. R. (1996). *Improving problem solving with illustrations and analogies: Novice mental models of the Internet (verbal analogies)*. Unpublished doctoral dissertation, University of Southern California.
- Thomson, W. (Lord Kelvin), & Tait, P. (1903). *Treatise on natural philosophy*, 2 vols. Cambridge: Cambridge University Press.
- Toulmin, S. (1953). *The philosophy of science: An introduction*. London: Hutchinson's University Library.
- Toulmin, S., & Goodfield, J. (1962) *The architecture of matter*. Chicago: University of Chicago Press.
- Turbayne, C. M. (1970). *The myth of metaphor*. Columbia: University of South Carolina Press.
- Tyner, K. (1998). *Literacy in a digital world: Teaching and learning in the age of information*. Rahway, NJ: Erlbaum.
- Van Hartesveldt, F. (1998). The undergraduate research paper and electronic resources: A cautionary tale. *Teaching History: A Journal of Methods*, 23(2), 51-59.
- Vincent, S., & Norman, S. K. (Eds.). (1999). *All that glitters: Prospecting for information in the changing library world*. Stamford, CT: JAI Press.
- Wellisch, H. (1995). *Indexing from a to z*, 2d ed. New York: H. W. Wilson.
- Whyte, L. L. (1961). *Essay on atomism: From Democritus to 1960*. Middletown, CT: Wesleyan University Press.
- Wolf, A. (1935). *A history of science, technology, and philosophy in the 16th and 17th centuries*. London: George Allen & Unwin.
- Wolpert, L. (1992) *The unnatural nature of science*. Cambridge: Harvard University Press.